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Baryogenesis in a supersymmetric model with Z_3 matter parity

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We analyze a scenario for baryogenesis at low temperature (~ 1 TeV) in supersymmetric extensions of the standard model. These extensions contain gauge singlets and discrete symmetries that suppress unwanted baryon- and lepton-number violation, and offer a framework to accommodate nonstandard neutrino physics. In our scenario, the decay of the lightest supersymmetric particle generates a net lepton number that is subsequently converted, via anomalous electroweak processes, into baryon number. We find that this possibility could be realized in models incorporating a Z_3 discrete symmetry, although it requires a scalar singlet as the lightest supersymmetric particle and a somewhat complicated pattern of couplings and fields in the singlet sector.

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I. INTRODUCTION

The minimal supersymmetric extension of the standard model (MSSM) [1] contains a discrete symmetry known as R parity (R_p) under which all the supersymmetric (SUSY) fields (squarks, sleptons, Higgsinos, and gauginos) change sign while the standard particles remain unchanged. This symmetry forbids operators with an odd number of SUSY fields and implies that the lightest SUSY particle (LSP) is stable. In terms of the superpotential P the MSSM can be written as

$$P_{\mathrm{MSSM}} = y_u\, qu^c h + y_d\, qd^c h' + y_e\, le^c h' + \mu\, hh' , \qquad (1)$$

where $q \equiv (u\ d)$, $l \equiv (e\ \nu)$, $h \equiv (h^0\ h^+)$, $h' \equiv (h'^-\ h'^0)$, and the respective fermions are two-component spinors of left-handed chirality (family indices are omitted). There are other renormalizable gauge-invariant terms that could appear in P,

$$P' = y_1\, u^c d^c d^c + y_2\, qd^c l + y_3\, lle^c + \mu'\, lh , \qquad (2)$$

but they would predict processes with lepton (L) and baryon-number (B) violation and their couplings must be suppressed from phenomenological arguments. These terms would induce R_p-violating operators and are absent in the minimal model.

R_p can be understood as a discrete symmetry of the superpotential called matter parity (MP). The usual MP is a Z_2 [2] symmetry (see Table I), but it is possible to define $Z_n (n=3,4,..)$ [3] symmetries with the same effect: to forbid the terms in Eq. (2) while allowing the MSSM. Although equivalent at the renormalizable level, the Z_2 and Z_n cases are different if one assumes the fields and vacuum expectation values (VEV's) of grand unified scenarios. For instance, after integrating out these fields, the effective model with Z_3 symmetry in Table II includes dimension-six operators of type $d^c d^c d^c ll$ (not present in the Z_2 case, where R_p is exact) producing LSP decay. However, to be consistent with the lifetime of the proton and also to keep the successful perturbative unification of the MSSM [4], one expects this extra physics at very high energies ($\gtrsim 10^{15}$ GeV). In that case the lifetime of the LSP is too long to be measured or to be cosmologically relevant, and Z_2 and Z_3 MP's are equivalent R-parity models.

In addition to the constraints from proton decay and other particle physics experiments, there is another generic argument (as pointed out in Ref. [5]) that strongly suggests the presence of an R_p in SUSY models. It has recently become clear [6] that anomalous electroweak (EW) processes violating $B+L$ are unsuppressed and in thermal equilibrium in the early Universe, at temperatures $T \gtrsim 100$ GeV (and probably up to 10^{12} GeV) [7]. The R_p-violating operators derived from Eq. (2) do not conserve L and B; if they were in thermal equilibrium while these anomalous processes are effective, any primordial baryon asymmetry would be erased. This argument constrains some of the couplings in Eq. (2) more than any particle physics experiment [5,8], and it has also been used to limit possible Majorana masses (which would imply processes with $\Delta L = 2$) [9].

From the model-building point of view, the MP's ap-

TABLE I. Z_2 matter parity.

Field	Z_2	Field	Z_2
$(e\ \nu)_i$	-1	$(h^0\ h^+)$	$+1$
$e^c i$	-1	$(h'^-\ h'^0)$	$+1$
$(u\ d)_i$	-1	n_+	$+1$
u_i^c	-1	n_-	-1
d_i^c	-1		

TABLE II. Z_3 matter parity ($\alpha^3=1$).

Field	Z_3	Field	Z_3
$(e\ \nu)_i$	1	$(h^0\ h^+)$	α^2
e_i^c	α^2	$(h'^-\ h'^0)$	α
$(u\ d)_i$	1	N	α^2
u_i^c	α	N^c	α
d_i^c	α^2	n	1

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pear naturally in some grand unification scenarios, whose gauge structure incorporates them automatically [10], or in superstring models, where they appear as a combination of a gauge and a discrete symmetry of the compactified model [3].

Extensions in MP scenarios can be obtained by the addition of light nonstandard superfields. In particular, we will consider in this paper a Z_2 and a Z_3 MP model extended by the presence of gauge singlet superfields. The physical interest of this type of extension is twofold. In principle, the addition of gauge singlets provides a *soft* way to break R_p: while all the terms in Eq. (2) are still forbidden, new R_p- and L-violating terms involving these singlets may appear. Our scenario for baryogenesis will be derived from those new terms. On the other hand, experimentally there is still room in the neutrino sector for nonstandard physics (neutrino masses [11] or an anomalous large τ lifetime [12]). Furthermore, this type of extension will not modify the consistent lifetime of the proton or the gauge unification predicted by the MSSM, and can be implemented in most of the grand unification theories.

To build our models, first we add all possible singlets with $Z_{2,3}$ numbers. We find their couplings with the other fields allowed by the MP and the gauge symmetry and assign them lepton numbers. We then define an extended R-parity which includes the new fields, and we study the relation between R_p violation and L violation. We expect to find a scenario where all the R_p-violating operators that allow the LSP to decay also violate the lepton number. We show that this leads to an interesting framework for leptogenesis in these models, provided that the conditions for out of equilibrium and for sufficient CP violation are satisfied. If leptogenesis takes place in the early Universe at temperatures where nonperturbative $(B+L)$-violating processes are effective, this net lepton number could be partially transferred [6,13] into baryon number and define the baryon asymmetry of the Universe (BAU).

II. MODELS WITH Z_2 MATTER PARITY

The $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlets n_+ and n_- carry $+1$ and -1 Z_2 numbers, respectively (see Table I). The singlet n_+ allows in P terms of type n_+hh', as well as bilinears n_+^2 and trilinears n_+^3. The coupling with two Higgs doublets defines $L(n_+)=0$ and assigns positive R_p to the scalar component and negative to the fermion. None of these three couplings break R_p (or L), and hence the LSP remains stable.

Singlets of type n_- can couple to Higgs and lepton doublets in trilinears of type n_-lh. They carry lepton number, $L(n_-)=-1$. The scalars are R_p odd and the fermions R_p even (in contrast with n_+). The mass term n_-^2 in P would be allowed by the symmetries, and also trilinears $n_-^2 n_+$, if both types of singlets are present. In this framework, R_p is still an unbroken symmetry and the LSP stable, so the proposed scenario for baryogenesis cannot be realized.

The Z_2 models considered in this section contain a source of L violation in the Majorana mass of the neutrino n_- (and also in the dimension-4 operators derived from $n_-^2 n_+$). These terms could erase any primordial baryon number unless the couplings in n_-lh are very suppressed and/or the fields n_- are very heavy ($\geq 10^7$ GeV). In that case the Z_2 MP model can accommodate scenarios where the BAU is generated through the decay of the heavy Majorana neutrino n_- (as proposed by Fukugita and Yanagida [13]), the decay of the sneutrino $\tilde{n}_-$ [14], or via condensate oscillations along flat directions of the scalar potential [15].

III. MODELS WITH Z_3 MATTER PARITY

There are two inequivalent Z_3 MP's [3] that forbid all the terms in Eq. (2), but both of them lead to the same type of model. We shall consider the MP defined in Table II. Here three different types of singlets can appear: N, N^c, and n, with respective Z_3 numbers α^2, α, and $1(\alpha^3=1)$. The complete structure of the superpotential is

$$P=P_{\rm MSSM}+m_N NN^c+m_n n^2+y\, lhN^c+z\, hh'n$$
$$+\lambda_1 N^3+\lambda_2 N^{c3}+\lambda_3 n^3+\lambda_4 nNN^c \ . \quad (3)$$

In addition, we will assume the usual soft SUSY-breaking terms of supergravity models (scalar and gaugino masses of order 1 TeV plus a scalar term proportional to P).

The chiral superfield n couples with two Higgs doublets; hence, it does not carry the lepton number. As in the Z_2 case, the fermion component is R_p odd (corresponding to a SUSY particle), while the scalar is R_p even. The fermion defines a nonweakly interacting Majorana neutrino.

The fields N and N^c combine in a mass term of type $m_N NN^c$, and they couple to lepton and Higgs doublets. Their respective lepton numbers are $+1$ and -1. For both superfields the scalar component is SUSY $(R_p=-1)$, while the respective fermions define a R_p-even Dirac neutrino which is also nonweakly interacting before the EW phase transition.

We observe that the trilinears N^3 and N^{c3}, the only terms which break R_p, are also the only source of L violation $(\Delta L=\pm 3)$. If the LSP decays, it will be through a process mediated by these operators, which could be relevant for leptogenesis.

Before analyzing the possibility of baryogenesis in this scenario, we would like to briefly review its particle physics motivation. The coupling of the singlets N and N^c in Eq. (3) have been proposed as an interesting extension of the neutrino sector of the SM. Before the EW phase transition they define a Dirac field of mass m_N with $N_L\equiv N$ and $N_R^c\equiv N^c$. After the Higgs scalars develop VEV's, the couplings $h\nu_i N^c$ mix N with ν_i (i is a family index), defining a heavy Dirac field plus three massless neutrinos. Remarkably, the symmetries of the model provide a mass matrix where the three basically standard neutrinos remain massless for all values of the mixing between the nonweakly interacting and the weakly interacting sectors. In contrast with extensions of the standard model with Majorana fields, a mixing of order 0.1 would not violate the lepton number (which would erase any baryon asymmetry) or make the weakly interacting neutrinos massive (which is disfavored by cosmological arguments based on nucleosynthesis and the age of the Universe [16]). Sizable mixings in the lepton sector could be used to accommodate a τ lifetime slightly longer than expected in the standard model, a possibility still suggested by some experiments (see Refs. [12,17]). This type of extension of the standard neutrino sector has been proposed with a structure based on global symmetries [18], also in the framework of left-right-symmetric models [19], and recently (with only one pair of singlets) in MP models derived from the heterotic string [17]. We will consider here the generic model with one or several families of singlets N, N^c, and n, with the symmetries previously described.

IV. BARYOGENESIS IN THE Z_3 MODEL

The scenario that we intend to implement is as follows. First, the out of thermal equilibrium (OTE) decay of the LSP generates a net lepton number. Subsequently, thermal $(B+L)$-violating processes partially transfer this lepton excess into a baryon asymmetry, with $n_B=\frac{28}{79}n_L$ [20].

N^3 and N^{c3} are the only terms in P that violate R_p, with vertices containing one SUSY scalar plus two nonweakly interacting neutrinos. As a consequence, the decay of the LSP will necessarily involve the (real or virtual) decay of one (or both) of the SUSY scalars in the singlet sector. Let us assume that $\tilde{A}_1=c_\theta\tilde{N}+s_\theta\tilde{N}^c$ is the LSP and has a mass m_1 greater than the critical temperature of the EW phase transition T_c. (A tilde indicates R_p-odd states: squarks, sleptons, Higgsinos, gauginos, the scalar components of N and N^c, and the fermion component of n.) To generate a lepton asymmetry from its decay, there are several conditions that must be satisfied [21,22]. First, the decay must violate L. Second, when the temperature of the Universe drops below $T=m_1$ the decay rate (i.e., the inverse lifetime) must be smaller than the expansion rate of the Universe. To guarantee overabundance when $\tilde{A}_1$ decays, it is also necessary that all other processes that change its number are OTE as well. In addition, after the decay and as long as the EW anomaly is effective, all $B-L$ violating processes must be also OTE. Finally, C and CP must be violated at the appropriate rate.

A_1 decays into two massive antineutrinos $\bar{N}$ in a process with $\Delta L=-3$. On dimensional grounds, the decay rate at $T\lesssim m_1$ is of order $\Gamma_D\sim\lambda^2 m_1$, where $\lambda\sim\lambda_1,\lambda_2$, while the expansion rate of the Universe is $H\sim\sqrt{g_*}T^2/M_{\rm Pl}$ ($g_*\sim 10^2$ is the effective number of relativistic degrees of freedom). The inverse decay will be ineffective if $\lambda\lesssim 10^{-8}$. For such a coupling all the scattering processes with L violation will be out of equilibrium since all of them are proportional to λ^2.

The terms derived from $y\,hlN^c$ in P are in principle unsuppressed ($y\gtrsim 10^{-2}$ if one intends to explain an anomaly in the τ lifetime), but they do not break R_p and are irrelevant in the decay of $\tilde{A}_1$. However, it is necessary that $y\gtrsim 10^{-7}$ in order to keep the singlets in thermal contact with the other fields; if this constraint were not satisfied, then the relative abundance of scalar particles $\tilde{A}_1$ at $T\gtrsim m_1$ would require further hypothesis to determine, and the lepton number carried by the heavy neutrinos would *not* be effective, making impossible the proposed mechanism for baryogenesis.

Let us now consider the other OTE conditions. The scattering processes that change the number of scalars $\tilde{A}_1$ are kinematically disfavored below $T=m_1$. The inelastic scattering of $\tilde{A}_1$ with a massless standard field must have a SUSY particle in the final state; otherwise it is suppressed by powers of λ. Since $\tilde{A}_1$ is the LSP, the scattering processes are exponentially suppressed by Boltzmann factors at temperatures below m_1.

The annihilation processes, for example, into two Higgs bosons $h\bar{h}$ or to a pair $\nu\bar{\nu}$ via Higgsino $\tilde{h}^0$ in the t channel, turn out to be the only ones that could keep an equilibrium number of scalars $\tilde{A}_1$, since they are not necessarily proportional to λ^2. The cross section of these processes is proportional to y^4, and a consistent suppression requires that $y\lesssim 10^{-4}$. This suggests that, in addition to the singlets relevant in τ physics (or possibly instead of them), we need a second pair of singlets (N,N^c) whose scalar components define the LSP.

Note that the annihilation rate is proportional to the number density of particles, and its OTE condition may not necessarily be satisfied at $T=m_1$. One could obtain a viable framework if, for example, $\Gamma_{\rm ann}\sim 10^2 H$ at that temperature, in which case the freeze out would be expected when the number density of particles has been reduced (via annihilations) by two or three orders of magnitude. This reduction and the subsequent overabundance would be achieved fast for $T<m_1$, since the equilibrium distribution drops exponentially. Note, however, that the predicted ratio n_B/s would then be diminished by the same reduction factor.

We observe also that the LSP should not be any of the standard fields, since all of them contain annihilation modes which are too effective. If the LSP carried gauge numbers or had Yukawa couplings $\gtrsim 10^{-2}$, the freeze out would occur after annhiliations had reduced the ratio $n_{\rm LSP}/s$ by a factor $\lesssim 10^{-8}$, and the lepton asymmetry obtained from the decay would be far too small.

Let us finally estimate the lepton asymmetry generated from the decay of $\tilde{A}_1$. We need at least two different decay modes, each one with different L violation. A net lepton number will appear if there is an asymmetry between the branching ratios of these and the CP conjugate decay modes of the antiparticle [22].

In this model, however, the only decay processes allowed by R_p are of types (in terms of two-component spinors) $\tilde{A}_1 NN$ and $\tilde{A}_1\bar{N}^c\bar{N}^c$. To obtain different decay modes, it is necessary to introduce another pair of singlets, (N',N'^c), very weakly coupled with lepton and Higgs doublets. If at a given temperature the corresponding Dirac neutrino is not in thermal contact with quarks and leptons, then its effective lepton number is zero, and $\tilde{A}_1\to\bar{N}\bar{N}$ $(\Delta L=-3)$ and $\tilde{A}_1\to\bar{N}'\bar{N}$ $(\Delta L=-2)$ define two modes with different L violation. We need this condition to hold as long as $B+L$ violating processes are in thermal equilibrium. Once the EW phase transition has taken place and these processes are not effective, N' may

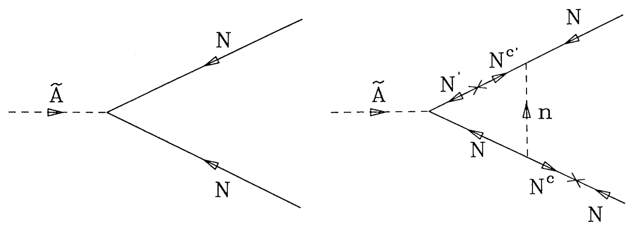

FIG. 1. The tree-level and the one-loop diagram relevant for *CP* violation. The fields are two-component spinors (solid) and complex scalars (dashes). The arrow indicates flux of quantum numbers carried by the particle and the cross a mass insertion.

decay into $\nu f \bar{f}$.

CP violation can occur, for instance, through the interference between the tree-level and the one-loop diagrams in Fig. 1. The relevant couplings in these diagrams involve only gauge singlets ($\tilde{A}_1 = c_\theta \tilde{N} + s_\theta \tilde{N}^c$):

$$P = m_N N N^c + m_{N'} N' N^{c'} + m_n nn + \lambda_1 N^3 + \lambda_4 n N N^{c'} + \lambda_1' N^2 N' + \lambda_4' n N N^{c'} \ . \quad (4)$$

We find that

$$\Gamma(\tilde{A}_1 \rightarrow \overline{N}\overline{N}) - \Gamma(\overline{\tilde{A}}_1 \rightarrow NN) = 4|c_\theta|^2 \mathrm{Im}(I_{NN'} \mathrm{Im}(\lambda_1^* \lambda_1' \lambda_4^* \lambda_4') \ , \quad (5)$$

where the phase-space factor $I_{NN'}$ will be complex if the intermediate particles in the loop are allowed to propagate on mass shell ($m_1 > m_N + m_{N'}$, note that m_1 includes soft-mass contributions). Taking into account the two decay modes, the net lepton number produced is

$$\mathcal{E}_{\tilde{A}_1} = \frac{4}{\Gamma_{\tilde{A}_1}} |c_\theta|^2 \mathrm{Im}(I_{NN'}) \mathrm{Im}(\lambda_1^* \lambda_1' \lambda_4^* \lambda_4') \times [\Delta L(\tilde{A}_1 \rightarrow \overline{N}\overline{N}) - \Delta L(\tilde{A}_1 \rightarrow \overline{N}\overline{N}')] \ . \quad (6)$$

If the coefficients in Eq. (4) are complex it will be impossible to absorb all their phases by field redefinitions, and the product in Eq. (6) will have an imaginary component. Since $\Gamma_{\tilde{A}_1} \sim \lambda_1^2 m_1$, assuming that $\lambda_1 \sim \lambda_1'$, the net lepton number created in the decay of each $\tilde{A}_1$ is of order $\mathcal{E}_{\tilde{A}_1} \sim (\lambda_4 \lambda_4')$, although there is also a possible suppression produced by the initial effectiveness of annihilation processes and a kinematical factor $m_N m_{N'}/m_1^2 \sim 10^{-1}$.

The couplings of $nNN^{c'}$ are constrained since they could thermalize the neutrino N' (all the operators which could define the lepton number of N' must be *ineffective* above 100 GeV). In particular, for the (R_p-conserving) processes $n + N' \rightarrow N$ and $\overline{N}' + N \rightarrow \overline{N}N$ to be suppressed, we must require that $m_n > m_1$ and $(\lambda_4 \lambda_4') \lesssim 10^{-6}$ (taking $m_n = 10 m_1$ and $T_c = 100$ GeV). This condition implies $\mathcal{E}_{\tilde{A}_1} \lesssim 10^{-6}$, allowing $\mathcal{E} \sim 10^{-8}$ as required for baryogenesis.

V. SUMMARY AND CONCLUSIONS

We have considered a possible scenario for baryogenesis in MP models with extra singlets. We have found a Z_3 framework where the R parity and lepton number are broken by the same operators, so it is *natural* to obtain L violation from the decay of the LSP. However, acceptable annihilation rates are obtained only if all the couplings of the LSP are small ($\lesssim 10^{-4}$), implying that the LSP must be one of the nonstandard singlets. In addition, the need for several decay modes with different L violation (to generate a net lepton number) leads to the inclusion of a pair of singlets very weakly coupled, such that the corresponding Dirac neutrino is not in thermal contact with the other fields and decays when the $B + L$ violating processes are not effective.

A consistent pattern of masses and couplings in the singlet sector would consist of three pairs of singlet superfields (N, N^c). The first pair, with couplings $N^c lh$ in P of order $\gtrsim 10^{-2}$ and sizable mixing with the EW neutrinos, would possibly be the one relevant in τ physics. The other two pairs might have analogous trilinears with couplings of order 10^{-4} and $\lesssim 10^{-6}$, and their scalar sector should contain the LSP (the mixing of the LSP $\tilde{A}_1$ with the scalar in the first family should be $\lesssim 10^{-2}$). The trilinears combining the three generations of singlets should be of order 10^{-8}. The masses of the heavy nonweakly interacting neutrinos could be of order 100 GeV, while the LSP should have a quite heavy mass (we estimate that $m_1 \gtrsim 400$ GeV), since it must decay when the anomalous EW processes are still effective. Note that the LSP is constrained to have a lifetime between 10^{-12} s (condition for overabundance) and 10^{-10} s (decay before T_c).

This scenario is by no means simple. However, the possibility of baryogenesis at the SUSY scale seems quite interesting, especially since it involves the range of energy to be explored in the near future.

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